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LCA FOR RENEWABLE RESOURCES

Life cycle assessment of densified wheat straw pellets in the Canadian Prairies

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Abstract

Purpose Densification, a process used to manufacture pellets in order to increase biomass bulk density, plays a crucial role in the economics of biomass utilization. The Canadian Prairies produce large quantities of agricultural residues each year, in particular wheat straw. This study performs life cycle assessment of wheat straw pellets by evaluating environmental effects of the entire pellet production system comprising feedstock production (on-farm wheat straw production), harvesting, baling, transportation, and the industrial processing involving drying, grinding, pelletizing, and packing in the densification plant. The effects of each process on the environmental performance of wheat straw pellets were investigated.

Methods This study was conducted using LCA software and incorporating the Ecoinvent database supplemented with literature data for the Canadian Prairies. Wheat straw pellets manufactured from the densification plant are evaluated with respect to their use of resources and energy consumption. Environmental emissions associated with the agricultural processing and manufacturing systems are quantified. Sensitivity analysis is conducted to compare allocation methods and investigate the environmental impact of pelletizing and drying processes. The functional unit is defined as 1 kg wheat straw pellet.

Results and discussion The study quantified the environmental impact of producing wheat straw pellets in terms of global warming potential, acidification, eutrophication, ozone layer depletion, abiotic depletion, human toxicity, photochemical oxidation, fresh water aquatic ecotoxicity, and terrestrial ecotoxicity. Drying, pelletizing, and fertilizer are the main contributors to global warming, acidification, abiotic depletion, human toxicity, terrestrial ecotoxicity, photochemical oxidation, and most of the other environmental impacts. Wheat seed has more impact on eutrophication. Transportation has an impact on ozone layer depletion, while grinding has an effect on freshwater aquatic ecotoxicity.

Conclusions The environmental impact of materials and energy fluxes on producing wheat straw pellet in the Canadian Prairies is assessed. The effect of each processing step on the entire manufacturing process is described. Overall, drying and pelletizing processes contribute the most environmental burdens except eutrophication and terrestrial ecotoxicity which are dominated by agricultural fertilizer/seed utilization and harvesting. In order to mitigate the environmental impact of wheat straw pellet production, minimizing energy consumption and machinery burdens from the drying and pelletizing processes are the main intervention points for wheat straw densification. Fertilizer production and utilization are key variables in strategies to lower eutrophication and terrestrial ecotoxicity.

Keywords Canadian Prairies · Densification system · Energy consumption · Life cycle assessment · Pellet · Wheat straw

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1 Introduction

Biomass is a renewable resource for production of biofuels and other biochemicals that substitute traditional chemical

products derived from nonrenewable fossil feedstocks (Eisentraut 2010; Clark and Deswarte 2008). Potential biomass sources include waste products from forestry and agricultural residues, municipal solid waste, and energy crops. It is estimated that 123 million dry tonnes of biomass is available in Canada (Kumarappan et al. 2009). Agricultural residues are the cheapest and most abundantly available biomass source in Canadian Prairies, while forest and mill residues are more available in British Columbia and Quebec. One of the major limitations for biomass utilization is the difficulty of storage and transportation because of its low bulk density. Typical bulk density of agricultural biomass and woody biomass is 60–80 and 200–400 kg m^{-3}, respectively (Tumuluru et al. 2010). The bulk density of biomass can be increased by forming pellets or briquettes, which results in a final compact density of 600–1,200 kg m^{-3} (Adapa et al. 2009). In addition, densified products have lower moisture content, uniform shape and size, which facilitate easy handling and transportation using standard transportation and storage equipment, resulting in lower industry operational cost. In addition, densified biomass can be effectively used for production of energy through combustion, biofuel, gasification, and other chemical conversion processes. Wood-based pellets have been commercially transported and utilized around the world because of their higher bulk density relative to agricultural biomass. The production of wood pellets has become a fast-growing industry in Canada's east and west coast, especially in British Columbia, where more than two thirds of Canadian wood pellets are produced. Compared with wood-based densification plants, there is very limited production of agricultural biomass-based pellets (Sultana et al. 2010). The Canadian Prairies (Alberta, Saskatchewan, and Manitoba) are abundant in agricultural residues rather than forestry residues, accounting for 90% of lignocellulosic agricultural residues. However, the region has not yet developed a clear biomass pellet supply chain. It is believed that biomass-based energy generates lower life cycle greenhouse gas emissions compared to grain-based ethanol and fossil fuel (Kumarappan et al. 2009). Since densification is a necessary step for biomass utilization, how the process and the whole system affects the environment is a pertinent issue. However, most studies have been conducted on biomass pellet characteristics and energy consumption (Tabil and Sokhansanj 1996; Mani et al. 2006a; Adapa et al. 2009, 2010), few studies focused on economic aspects (Mani et al. 2006b; Campbell 2007), very limited research focused on environmental impacts of wood pelletizing processes (Mani et al. 2005; Hagberg et al. 2009).

Life cycle assessment (LCA) is a systematic analytical method used to study environmental and other potential impacts of a specific process or a product's life from cradle to grave (Hendrickson et al. 2006). In other words, LCA enables analysts to estimate, quantify, and evaluate environmental burdens of a process or product over its entire life cycle in order to provide a comprehensive and consistent basis for comparing alternatives. Most LCAs on bioenergy are focused on agricultural cropping systems (Adler et al. 2007; Kim et al. 2009; Gasol et al. 2009), and bioethanol and biodiesel made from agricultural materials (Kim and Dale 2005; Spatari et al. 2010; González-García et al. 2010). A biomass densification system requires electricity and energy for processing, but the environmental impact of pellet production is scarcely studied. Mani et al. (2005) studied CO_2 emissions and the cost of pellet production using different fuels for the drying process. They found that using coal as fuel generated the highest environmental burden; wood pellets and dry sawdust were the best alternative fuel compared to natural gas and wet sawdust. They also concluded that more than 80% of the energy consumption was from the drying process. However, other studies analyzing energy consumption in densification systems found that the drying process accounted for only 43–69% of all process energy consumption (Jannasch et al. 2001; Sokhansanj and Fenton 2006). Therefore, there is need to conduct LCA for the entire pelletizing process beyond simply focusing on the drying process. Table 1 presents the distribution of energy consumption associated with unit processes involved densification systems based on previous studies (Jannasch et al. 2001; Pastre 2002; Sokhansanj and Fenton 2006; Adapa et al. 2010, 2011).

Wheat is the dominant crop in the Canadian Prairies and accounts for more than 90% of total Canadian wheat production. In this study, wheat straw is selected as the biomass to estimate the environmental impact of the densification system. The impact of the agricultural system (including seeding, fertilizing, harvesting, and baling) and the densification system (including drying, pelletizing, packing, etc.) on pellet environmental performance is investigated. This study aims to describe and quantify resource use and environmental impacts associated with the entire life cycle of wheat straw pellet production.

2 Methods

2.1 Goal and functional unit

The goal of this study is to analyze the environmental impact of biomass (wheat straw) pellet production in the Canadian Prairies. LCA software SimaPro 7.2 (Pré Consultants, Amersfoort, Netherlands) is used to conduct the life cycle analysis following the ISO 14040 and 14044 (International Organization for Standardization 2006). The 'CML 2 baseline 2000 (and Normalisation-world 1995)' method was selected in modeling the system performance. Environmental impact factors including global warming, acidification, eutrophication, ozone depletion, abiotic depletion,

Table 1 Energy consumption in biomass densification systems based on previous studies

Process	Energy consumption (kWh $tonne^{-1}$)			
	Jannasch et al. (2001)	Pastre (2002)	Sokhansanj and Fenton (2006)	Adapa et al. (2010, 2011)
Bale breaking and chopping	14.9	10–30		2.1
Fine grinding	55.9		27.8	12.3–42.6
Drying	347		97.2	
Pelletizing	74.5	30–60	74.4	82.5–105.8
Unloading bales, cooling	12.8			
Cooling		5	3.6	
Screening			1.7	
Bagging/packing			1.7	
Storage			7.2	
Miscellaneous equipment		10–20	14.4	

human toxicity, fresh water aquatic ecotoxicity, terrestrial ecotoxicity, and photochemical oxidation are analyzed. The environmental impact factors and evaluation units are based on methodology developed by Heijungs et al. (1992) and Guinée (2002). The definition of impact categories, IC_i, can be formalized using the equation $IC_i = \sum_j E_j CF_{ij}$ where E_j represents emissions of jth resource and CF_{ij} is the characterization factor and represents the relative contribution of jth compound to ith impact category (Udo De Haes et al. 1999). The functional unit is defined as 1 kg of wheat straw pellet produced from a densification plant.

2.2 System boundaries and densification system description

The system boundaries of this LCA are from cradle to gate. This includes the burden of all material inputs and agricultural/industrial processes from wheat straw biomass production to pellet production. Two subsystems, agriculture [subsystem 1 (S1)] and densification plant (subsystem 2), are described in Fig. 1. The grain produced from agricultural production is excluded from system boundaries.

After harvest, wheat straw biomass is baled and then transported over a certain distance to a densification plant. The transportation distance depends on the capacity of the pellet plant. In a pellet plant with a 5 to 10 tonne h^{-1} capacity, transportation distance from farm to pellet plant is assumed to be 15 km in the Canadian Prairies; this distance is reasonable based on biomass calculation from BIMAT (Agriculture and Agri-Food Canada 2010).

2.3 Data input and allocation

The Canadian Prairies are rich in biomass which is mainly from agricultural crop residues, with wheat straw being the most abundant. Therefore, this study takes spring wheat grown in Saskatchewan as the case to study the environmental impact of wheat straw production and densification in the prairie region.

2.3.1 Subsystem 1: agriculture system

Seeding rate and grain yield of spring wheat are collected from 3 years of field data by Johnston and Stevenson (2001) at Melfort, SK, which is 2,837 kg ha^{-1} wheat at an average seeding rate of 134 kg ha^{-1}. Total wheat straw yield is calculated according to a straw/grain ratio of 1.6 (Saskatchewan Agriculture and Food 2005). Because some straw has to be left on the field for soil conservation, only 70% of wheat straw is assumed to be collected, which is 3,177 kg ha^{-1}. Biomass provides nutrients when it is returned to the soil. When wheat straw is removed from the field, these nutrients have to be replaced by fertilizers. In Western Canada, 75% of farmers apply fertilizer based on crop nutrient removal rates established from previous government research or their own farming experience (Jensen 2009). Fertilizer value for western Canada is lower than eastern Canada, and there are no additional pesticides for wheat crops if the straw is removed (Henderson 2000). Nutrient content for 1 tonne wheat straw in Alberta is 8.6 kg N, 2 kg P, 18 kg K, and 1.5 kg S (Beyond Agronomy News 2009). These data are assumed to apply for the Canadian Prairies. Table 2 presents the quantity of fertilizer replaced when 1 ha of wheat straw is removed.

Biomass from agricultural residues is a by-product of grain production and agricultural processing. Therefore, allocation cannot be avoided in the agricultural subsystem. Mass allocation and economic allocation methods are considered in the agricultural system. Table 3 lists agricultural production inputs and operations common in the Canadian Prairies and the allocation of data in S1. It can be seen that wheat straw accounts for a larger percentage in grain/straw partitioning under mass allocation than economic allocation. Because economic values change with market conditions,

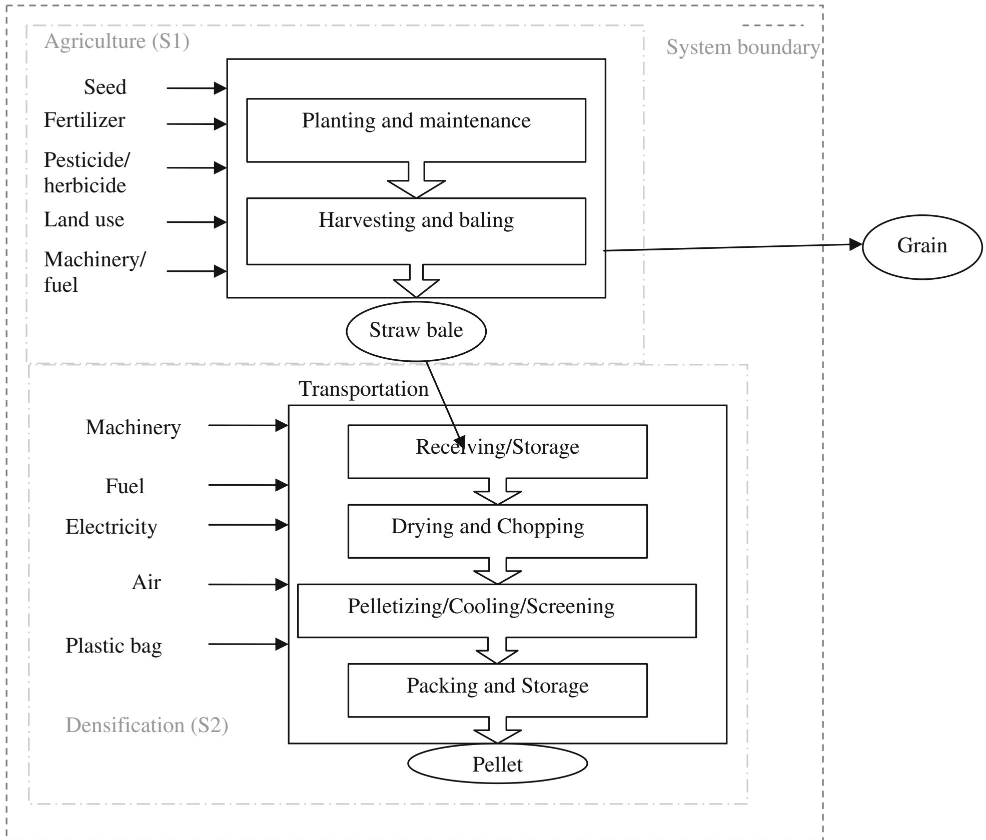

Fig. 1 System boundaries of producing biomass and making biomass pellet

mass allocation is used as the basis for analysis in this paper, entirely except sensitivity analysis of allocation methods.

From 1990, farmers began to adopt minimum tillage farming and one-pass planting and fertilization (Jensen 2009). In our study, zero tillage is adopted. Currently, one-pass planting and side-banded fertilizer is the most common way to apply fertilizer in western Canada (Jensen 2009), which means seeding and fertilizer application occur simultaneously. Most farmers in Saskatchewan have not adopted irrigation and pesticides in their wheat cultivation. Melfort, SK is in the black soil zone. Moisture is rarely a limiting factor in the black or dark gray soil zones, therefore irrigation is not used during cultivation. After combine harvesting, the wheat straw is baled and transported to a densification plant.

2.3.2 Subsystem 2: densification

The densification plant (pellet plant) includes a series of operations: biomass bale receiving, drying, grinding, pelletizing, cooling and screening, packing, and storage. It is assumed that all biomass received is processed into pellets, there is no mass lost during processing. It is also assumed that the pellet plant has 20 operational years with a capacity of 81,600 tonnes per year, land use per kilogram of pellet in the densification system is 1.2×10^{-9} ha, and it is ignored in this study. The energy spent in pelletizing, cooling, screening, and miscellaneous equipment is adapted based on results of Sokhansanj and Fenton (2006) which focused on Canadian biomass collection and preprocessing enterprises. Transportation distance is set at 15 km in the Canadian

Table 2 Fertilizer replacements for removing wheat straw in a 1-ha field

Nutrients required for wheat straw	Nutrients content required (kg ha^{-1})	Fertilizer replacement for wheat straw removed	Fertilizer nutrients amount (kg ha^{-1})
N	27.3	Ammonium nitrate, as N,	10.1
		Urea, as N	10.1
		Diammonium phosphate, as N	2.9
		Ammonium sulfate, as N	4.2
P	6.4	Diammonium phosphate, as P_2O_5	6.4
K	57.2	Potassium chloride, as K_2O	57.2
S	4.8	Ammonium sulfate, as S	4.8

Table 3 Agricultural production inputs, operations, and allocation

	Total input	Mass allocation (%)		Economic allocation (%)	
		Grain	Straw	Grain	Straw
Wheat seed	134 kg ha^{-1}	47	53	87	13
Herbicides 2,4-D	0.5 kg ha^{-1}	47	53	87	13
Fertilizer replacement	1 ha	0	100	0	100
Land use	1 ha	47	53	87	13
Sowing	1 ha	47	53	87	13
Application of plant protection products	1 ha	47	53	87	13
Combine harvesting	1 ha	47	53	87	13
Baling[a]	4.5 p	0	100	0	100
Loading bale[a]	4.5 p	0	100	0	100

[a]Round bale=700 kg, hence 3,177 kg ha^{-1}=4.5 bales

Prairies based on agricultural residues computed using BIMAT (Agriculture and Agri-Food Canada 2010). To develop unit processes and use existing Ecoinvent data in SimaPro, the amount of equipment/machinery used in processes of drying, grinding, and packing is assumed to be similar to existing processes of grass drying, wood residue chopping, and food packing in Ecoinvent data system. Biomass moisture before pelletizing is around 12% wb. It is assumed that air cooling rate is 0.04 kg per 1 kg pellet (Fasina 1994), and 3% of moisture is lost during pelletizing. According to Ecoinvent report on life cycle inventories (Ecoinvent 2007), electricity consumption is 100% converted to waste heat released to the atmosphere. In the pelletizing process, heat waste emission to the air is 0.287 MJ per 1 kg pellet. Electricity production mix was based on an average utilization for Canadian Prairies in 2009, namely 39% from hydropower, 46% from coal, 13% from gas, and 2% from wind (Environment Canada 2011). The unit operation input data and assumptions for the densification plant are given in Table 4.

2.4 Sensitivity analysis

Sensitivity analysis is a systematic procedure to estimate the effects of various choices of methods and data on the outcome of LCA study (International Organization for Standardization 2006). The objective of sensitivity analysis in this study is to test all parameters that can strongly influence the final output of the study.

2.4.1 Allocation methods

In subsystem 1, the agricultural process has two outputs: grain and straw. Allocation is an important issue in LCA. The ISO 14040/44 series (2006) recommends avoiding allocation either by subdividing the unit process or by expanding the system. If the above approaches cannot be applied, allocation must be applied either through a physical relationship such as mass and energy content, or economic value of the products. In this study, mass allocation is applied. In order to understand the influence of allocation methods on LCA results, as Table 3 showed, economic allocation is also compared. The cost of wheat straw nutrients is US $28.35 per tonne (Beyond Agronomy News 2009). It is assumed that farmers would require compensation equal to about 1.5 times of the full nutrient value of the residue removed from their fields (Campbell 2007). The value of a tonne of wheat straw is US $42.50 for nutrient

Table 4 Data input for densification plant

Data input in pellet plant	Input number	Unit	Note
Wheat straw bale	1	kg	Data from S1
Transportation bale to pellet plant	15	kg km	Transportation distance is 15 km
Unloading bale	1	kg	
Storage	1	kg	Use “dried roughage store, nonventilated, operation” data
Drying	0.3	kg	The unit is in kilograms water evaporated at 110–120°C drying temperature.
Grinding	1	kg	Use “industrial residual wood chopping” data
Pelletizing	1	kg	Pelletizing, cooling, and screening energy are included.
Pellet packing	1	kg	Packing material need is 0.006 kg LDPE for 1 kg pellet, and transportation distance of LDPE bag is 500 km.
Electricity, medium voltage	0.0144	kWh	Miscellaneous equipment energy consumption

input. The Canada Western Red Spring Wheat price is US $311.36 per tonne according to the Canadian Wheat Board 2008–2009 (CWB 2010). It is assumed that 70% of wheat straw can be removed from farm land.

2.4.2 Pelletizing energy

The amount of energy spent in the pelletizing process as part of the densification system is based on a value reported by Sokhansanj and Fenton (2006). This represents pellet mill electricity consumed in Canadian densification plant. Various authors have reported total energy consumed by the pelletizing process ranging from 30 to 106 kWh (Jannasch et al. 2001; Pastre 2002; Sultana et al. 2010; Adapa et al. 2010). The purpose of the sensitivity analysis is to estimate the effect of pelletizing energy consumption on pellet product environmental performance. Waste heat associated with electricity consumption is also calculated. Three sets of energy consumption parameters (from low to high) used during pelletizing are selected as shown in Table 5.

2.4.3 Drying properties

Another important process is drying. Due to a lack of adequate wheat straw drying data, this study adapted Ecoinvent data (for grass pellets) for burning 5 MJ light fuel oil and consumption of 0.05 kWh electricity for evaporating 1 kg water, which is much higher than the data presented by Sokhansanj and Fenton (2006) but similar to the data by Mani et al. (2005). It is also assumed that 0.3 kg water is evaporated during drying when producing 1 kg of pellets. Sensitivity analysis compared two parameters in the drying process: (1) the impact of different fuels: coal, natural gas, wood pellets, and light fuel oil (this study) to pellet environmental performance, and (2) the effect of various initial moisture content levels of wheat straw on pellet LCA results. Initial moisture content of wheat straw before drying is assumed as 40%, 32% (this study), and 20% wb. The amount of water evaporated during the drying process is also given in Table 5.

3 Results and discussion

3.1 LCA results

Table 6 presents total life cycle impacts of wheat straw pellets in terms of the following impact categories: global warming, acidification, eutrophication, human toxicity, fresh water aquatic ecotoxicity, terrestrial ecotoxicity, ozone layer depletion, abiotic depletion, and photochemical oxidant formation. The results in Table 6 are given for two allocation methods: mass allocation and economic allocation. However, as noted earlier, the discussion of results is based on mass allocation, which was the methodology adopted in this study. Economic allocation is presented here only for comparison and sensitivity analysis. Results based on economic allocation are discussed under the Section 2.4. Figure 2 presents further results on environmental impacts under mass allocation.

3.1.1 Global warming potential

Total life cycle global warming potential (GWP) is computed in terms of CO_2 as the equivalent substance (hereinafter referred to as CO_{2eq}). The results show that a 1-kg wheat straw pellet generates 326 g CO_{2eq}. By comparison, Mani et al. (2005) and Magelli et al. (2009) reported 238 to 446 g CO_{2eq} from 1 kg of wood pellet. The results suggest similarities between wheat straw pellet and wood pellet densification systems in terms of their greenhouse gas emissions. GWP is mainly evaluated from three gases: CO_2, dinitrogen monoxide (N_2O), and methane (CH_4). The quantification of airborne emissions, waterborne emissions, and emissions to soil provides further basis for measuring environmental impacts of wheat straw pellet production. As the results in Table 7 show, airborne emissions from pellet production are the largest

Table 5 Parameter setting in sensitivity analysis for drying and pelletizing 1 kg wheat straw

Parameters	Energy consumption in pelletizing		
	Low (Pastre 2002)	This study (Sokhansanj and Fenton 2006)	High (Adapa et al. 2010)
Electricity of pelletizing (kWh)	0.0300	0.0744	0.1058
Heat waste (MJ)[a]	0.127	0.287	0.400
	Moisture removed during drying process		
	Low initial moisture content 20%	This study—initial moisture content 32%	High initial moisture content 40%
Moisture removed (kg)	0.10	0.30	0.47

[a] Heat waste calculation is based on assumptions of life cycle inventories (Ecoinvent 2007), and it includes pelletizing and cooling/screening heat waste

Table 6 Environmental impact of 1 kg wheat straw pellet

	Mass allocation method	Economic allocation method
Global warming (g CO_2 eq)	326.30	299.02
Acidification (g SO_2 eq)	1.48	1.27
Eutrophication (g PO_4 eq)	0.54	0.40
Human toxicity (g 1,4-DB eq)	84.79	67.84
Fresh water aquatic ecotoxicity (g 1,4-DB eq)	36.66	35.52
Terrestrial ecotoxicity (g 1,4-DB eq)	0.46	0.41
Ozone layer depletion (g CFC-11 eq)	3.44×10^{-5}	3.09×10^{-5}
Photochemical oxidation (g C_2H_4)	5.47×10^{-2}	5.11×10^{-2}
Abiotic depletion (g Sb eq)	2.24	2.10

contributor to GWP. The densification process is capital intensive, with significant use of machinery and fossil oil, resulting in high CO_2 and CH_4 emissions. The impact of processing and material inputs on pellet environmental performance is presented in Fig. 2 for each impact category. The drying process contributes 43% to total GWP, followed by pelletizing (16%), fertilizer (15%), and combine harvesting (6%). In the drying process, light fuel oil accounts for 92% of GWP while electricity accounts for 7.6%. This illustrates the importance of choosing environmentally friendly fuel in the drying process, as Mani et al. (2005) demonstrated in wood pellet processing. In the agriculture subsystem, GWP is mainly caused by fertilizer use (ammonium nitrate and urea) and combine harvesting. Since drying and pelletizing are major contributors to GWP, this study conducts as a sensitivity analysis of these two processes, with results presented in Section 3.2.

3.1.2 Acidification

Acidification refers to the emission of acidifying substances that have an impact on soil, groundwater, ecosystems, and materials. In this study, acidification is expressed in equivalent SO_2 emissions per functional unit. Most acid

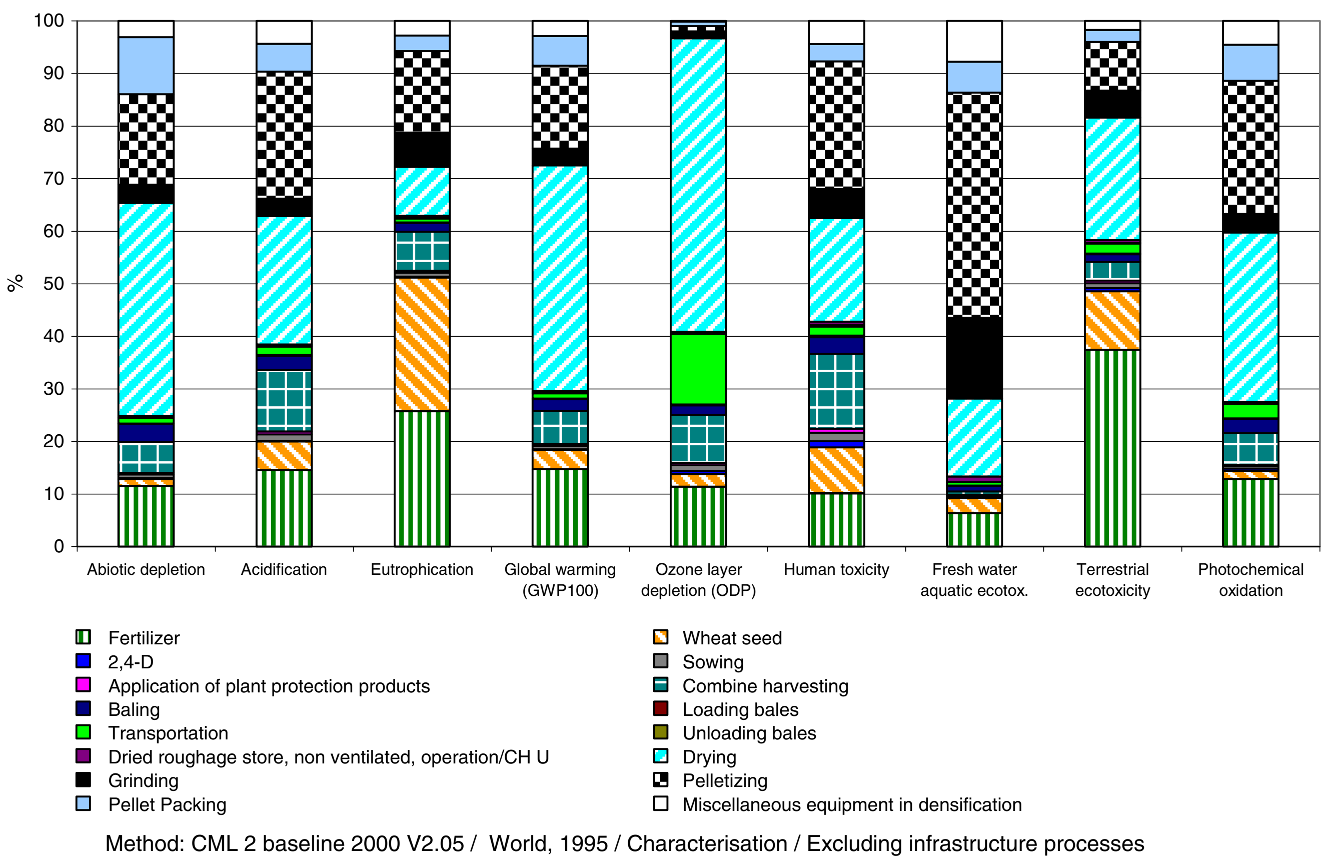

Fig. 2 Environmental impact of input and unit operation of producing wheat straw in bale

Table 7 Environmental impact indices of 1 kg wheat straw pellet (mass allocation)

	Airborne emissions	Waterborne emissions	Emissions to soil
Carbon dioxide, transportation (g CO_2)	3.11	–	–
Carbon dioxide, biogenic (mg CO_2)	823	–	–
Carbon dioxide, fossil (g CO_2)	284	–	–
Carbon dioxide, land transformation (mg CO_2)	7.21	–	–
Methane, transportation (mg CH_4)	5.29	–	–
Methane, biogenic (mg CH_4)	5	–	–
Methane, fossil (mg CH_4)	499	–	–
Methane, dichloro- (μg CH_4)	–	2.44	–
Methane, tetrachloro (pg CH_4)	–	33	–
Dinitrogen monoxide (mg N_2O)	92.5	–	–
Carbon monoxide, transportation (mg CO)	9.28	–	–
Carbon monoxide, fossil (mg CO)	184	–	–
Carbon monoxide, biogenic (μg CO)	395	–	–

deposition comes from SO_2 and NO_x generated by agricultural and industrial activities. The release of these substances combines with other atmospheric substances to produce acids and other compounds, notably acid rain which can lower soil and water pH, resulting in adverse impacts on ground water, fish, and forests. The results in Table 6 show that a 1-kg wheat straw pellet generates 1.48 g SO_2 eq in acidifying gases. This value is less than that for wood pellets which have reported amounts of 6.17–7.39 g SO_2 eq (Pa 2010; Magelli et al. 2009). The quantity of SO_2 and NO_x airborne emissions from 1 kg wheat straw pellet is 774 mg SO_2 and 879 mg NO_x as NO_2, respectively. SO_2 emissions are mainly caused by pelletizing (258 mg), drying (233 mg), and fertilizer (102 mg). NO_2 emissions are mainly a result of combine harvesting (294 mg), drying (162 mg), and pelletizing (94 mg). Figure 2 shows that drying and pelletizing contribute 24.4% and 24.2% to total acidification, respectively, while fertilizer and combine harvesting account for 14.5% and 11.7%, respectively.

3.1.3 Human toxicity

This impact category characterizes toxic chemicals with respect to human exposure. It is expressed in terms of the substance 1,4 dichlorobenzene (1,4-DB). The results in Table 6 show that a 1-kg wheat straw pellet generates 84.79 g 1,4-DB eq. This number is higher than that reported for wood pellets by Magelli et al. (2009). The reason might be due to the fact that SimaPro generates a fairly long list of substances combining emissions to the air and water that are poisonous to human beings (PRé Consultants 2008). By contrast, Magelli used human toxicity potential method developed by Huijbregts et al. (2000). The impact on human toxicity mainly comes from pelletizing (24.3%), drying (19.7%), combine harvesting (14.3%), fertilizer (10.2%), and wheat seed (8.7%). The use of coal and natural gas to generate electricity, coupled with the disposal of waste materials, are key factors in human toxicity.

3.1.4 Eutrophication

Eutrophication is measured in terms of PO_4 equivalents. It includes all impacts due to excessive levels of macronutrients in the environment caused by emissions of nutrients to air, water, and soil. The results in Table 6 show that a 1-kg wheat straw pellet generates 0.54 g PO_{4eq} emissions. Landfill disposal of industrial activities related to electricity, metal/machinery, and fuel production and utilization are key factors in eutrophication. The agriculture subsystem has the most impact on emissions of nutrients to the air, water, and soil. Fertilizer (25.7%), wheat seed (25.5%), and pelletizing (15.6%) are the main sources of eutrophication. Wheat seed has a high impact here because of fertilizer used for wheat grain production.

3.1.5 Other impact categories

Table 6 also lists other environmental impacts resulting from the production of 1 kg wheat straw pellet. Because there is no information from other studies to make a relative comparison, the analysis focuses on investigating how each processing stage affects environmental performance, as shown in Fig. 2. Abiotic depletion is related to human health and ecosystem health, which indicates the input of minerals and fossil fuels to the system (PRé Consultants 2008). Drying and pelletizing have the most impact on abiotic depletion. Drying also has the most impact on ozone depletion via emission of halogens and chlorofluorocarbons (CFCs), and photochemical oxidation due to fossil fuel use. Photo-oxidant formation (mainly ozone) is detrimental to human health and ecosystems, and may also damage crops. Transportation is another activity with an

impact on ozone layer depletion. Regarding water ecosystem, pelletizing accounts for 42.8% of total impact during the entire wheat straw pellet production process, with the remaining impacts coming from grinding (15.4%) and drying (14.8%). This is related to disposal of waste materials in each stage. Fertilizer use is the main contributor to impacts of toxic substances on terrestrial ecosystems, followed by drying. Therefore, it is important to use fertilizers more efficiently.

3.2 Sensitivity analysis

Sensitivity analysis is carried out to examine the effect of variations in system inputs on outputs. The sensitivity analysis focuses on two processes: drying and pelletizing. These two processes have demonstrated the most influence on the environmental performance of wheat straw pellet production.

3.2.1 Allocation methods

The choice of allocation method influences results. Table 6 compares environmental impacts generated using both mass allocation and economic allocation. Wheat straw has a lower market value than grain. Therefore, if economic allocation is used, wheat straw (the by-product from wheat grain production) would be ascribed a lower share in environmental impacts compared with mass allocation. This demonstrates that allocation criteria can affect LCA results; it also provides a rationale for sensitivity analysis when there is more than one allocation method. Allocation criteria in the order of physical relationships, economic values, and then physical quantities are recommended by ISO 14041 (International Organization for Standardization 1998).

3.2.2 Pelletizing energy

In order to investigate the effect of pelletizing energy on pellet environmental performance, three levels of energy consumption are assessed. The sensitivity analysis results presented in Fig. 3 show that 35% of fresh water aquatic ecotoxicity, 22% of photochemical oxidation, 21% of acidification and human toxicity, 15% of abiotic depletion, and 14% of global warming and eutrophication can be reduced when pelletizing energy is changed from a high level of 0.105 to a low 0.030 kWh kg^{-1}. There is no significant change in ozone layer depletion. The results indicate how pelletizing energy consumption can change the environmental impact of wheat straw pellet production.

3.2.3 Drying parameters

Figure 4 presents the effect of burning various fuels in the drying process on the environmental performance of the pellet

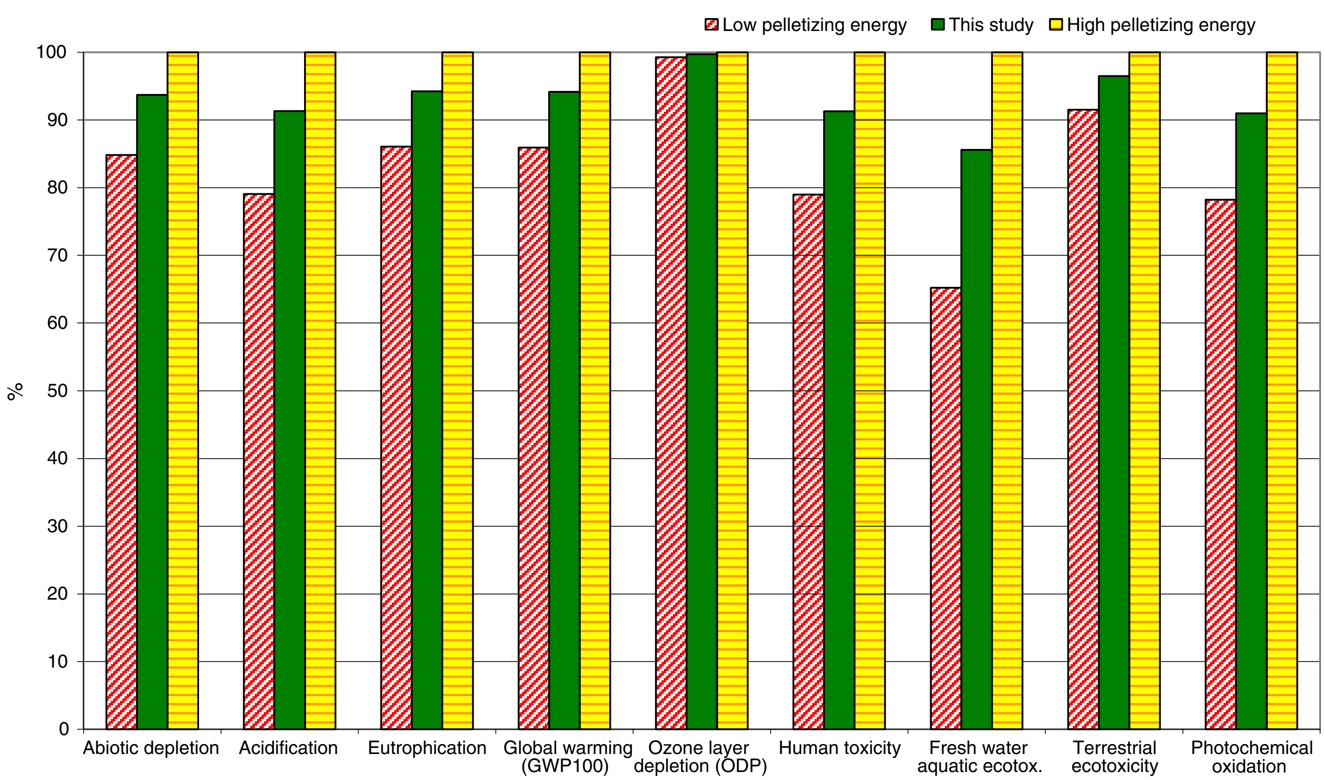

Fig. 3 Environmental impact of input and unit operation of producing wheat straw pellet

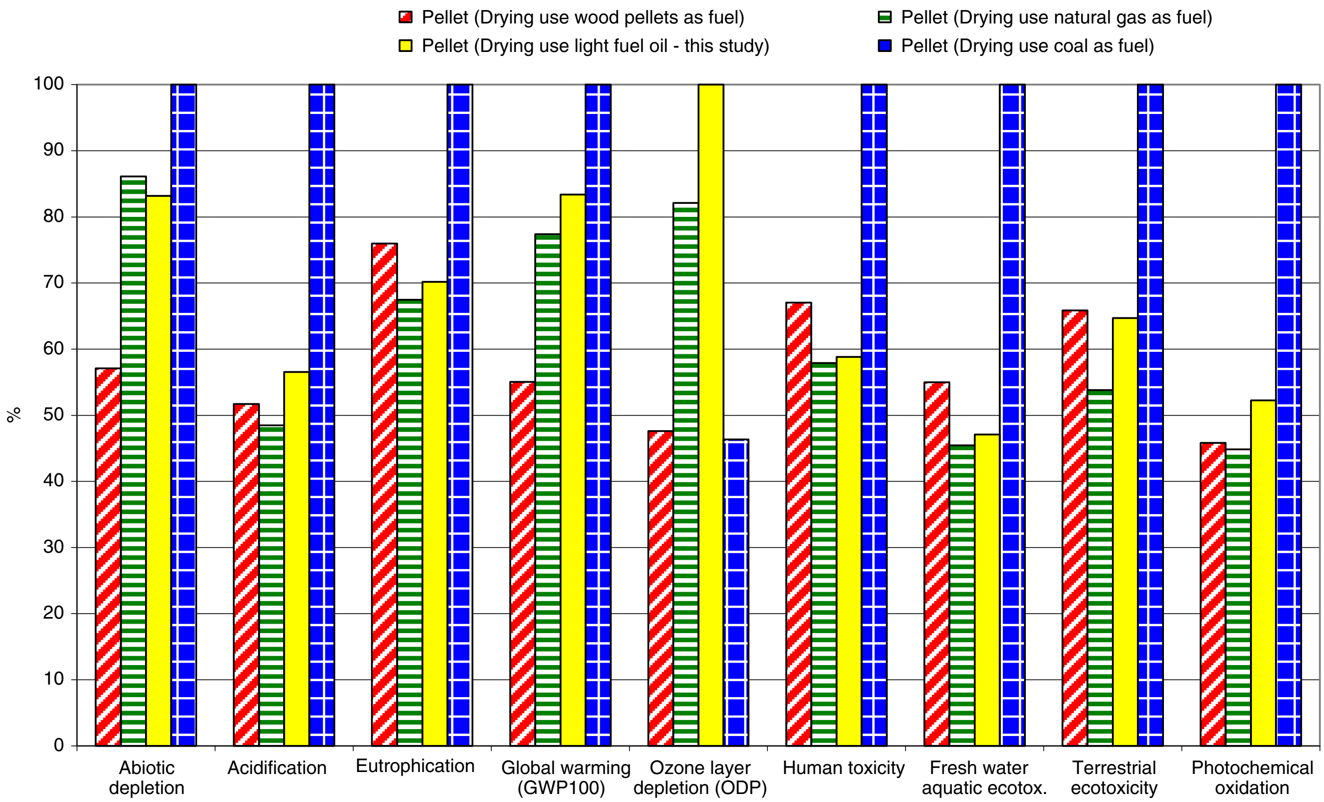

Fig. 4 The effect of pelletizing energy consumption on pellet product environmental performances

production system. Coal is the most polluting material, with the highest greenhouse gas emissions, acidification impacts, and almost all other categories. Mani et al. (2005) reported similar results when they compared LCA impacts of coal and other fuels for drying wood pellets. However, Fig. 3 shows that using coal as drying fuel has the lowest impact on ozone

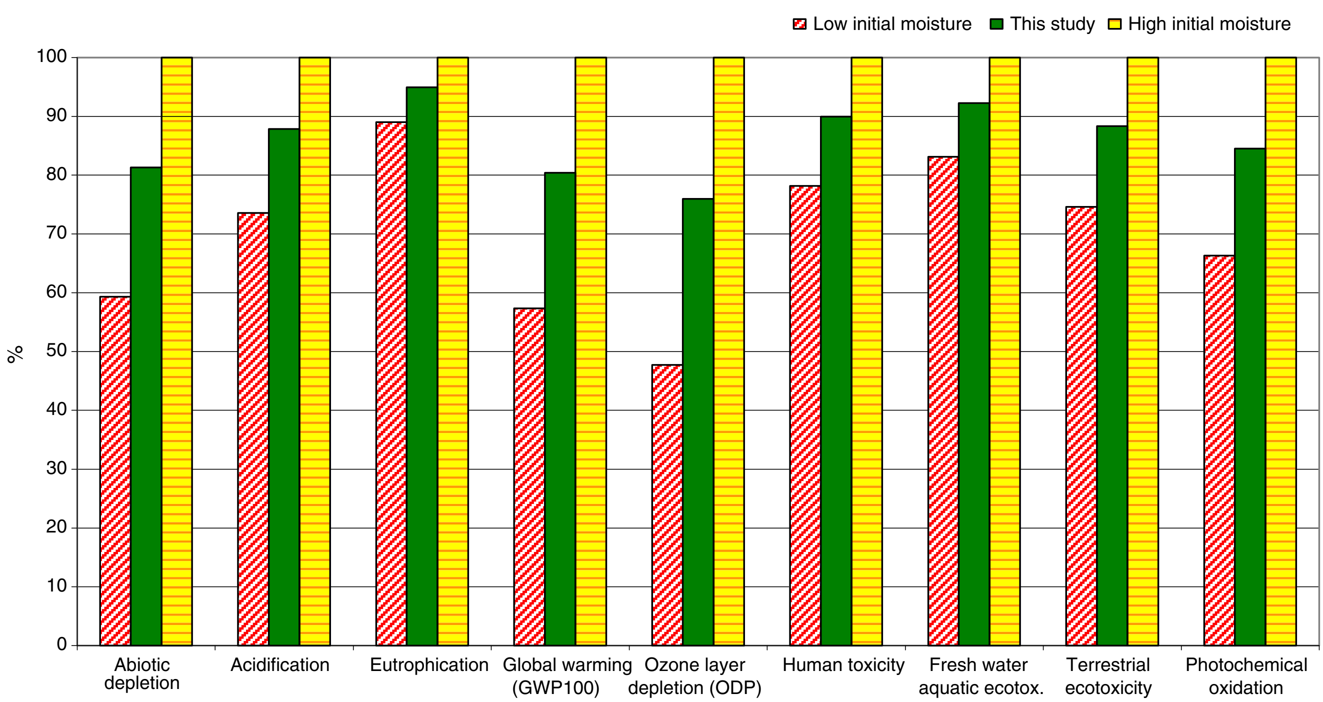

Fig. 5 The effect of initial wheat straw moisture content on pellet product environmental performance

depletion. The reason based on SimaPro is that the production process for light fuel oil, natural gas, and wood pellets generates more ozone-depleting substances than coal production. SimaPro not only computes data for input materials, it also calculates emissions from processes used to produce input materials. Therefore, the LCA results contain more information. Wood pellets have the lowest CO_2 eq emissions when used as a burner fuel in the drying process; natural gas and light fuel oil have lower CO_2 eq emissions than coal. It can be seen that using wood pellets as fuel in the drying system can reduce GWP by 45%, 28%, and 22% compared with coal, light fuel oil, and natural gas, respectively. Using wood pellets as burner fuel in the drying process also significantly decreased abiotic depletion. Compared to coal, the impact of wood pellets, natural gas, and fuel oil on other environmental categories did not show large variability.

During the wheat straw drying process, initial moisture content is another important factor influencing the environmental performance of pellets. This is because moisture content determines the total amount of water to be removed in the drying process and therefore energy consumption. A moisture content of 32% wb was adapted in this study. Figure 5 shows that GWP can be reduced by 23% if wheat straw initial moisture content is 20% wb, but increased by 20% if the initial moisture content is 40% wb. The same trend is observed for all other categories, demonstrating the importance of reducing wheat straw moisture content when the straw feedstock enters the densification plant. This can be accomplished through on-farm field drying and good transportation/storage management.

4 Conclusions

Densification is a process used to increase biomass density and therefore improve biomass storage and transportation for further biorefinery utilization. This paper evaluated the environmental performance of wheat straw pellets made in Canadian Prairies. Life cycle assessment results showed that producing 1 kg of wheat straw pellets generated a GWP of 326.30 g CO_2 eq, 1.48 g SO_2 eq, 0.54 g PO_4 eq, and 84.79 g 1,4-DB eq. This result is similar or slightly less than the environmental impact of wood pellets that has been published in Canada.

Wheat straw pellet production consists of growing wheat straw, harvesting, baling, transportation, and the industrial processing involving drying, grinding, pelletizing, and packing in the densification plant. The effects of each process on the environmental performance of wheat straw pellets were investigated. Overall, drying and pelletizing processes contribute the most environmental burdens except eutrophication and terrestrial ecotoxicity which are dominated by agricultural fertilizer/seed utilization and harvesting. The production and consumption of fossil fuels and electricity in unit operations are the main contributors to environmental burdens associated with a densification plant. Therefore, efforts must be focused on developing technologies and processes that improve efficiency in energy utilization in these energy-intensive drying and pelletizing processes.

In the agricultural production of wheat straw, fertilizer and harvesting are the major cause of environmental burdens, especially fertilizer, which contributes to GWP (essentially CO_2, CH_4, N_2O emissions), causing nitrogen emissions, nitrate leaching, and potassium and phosphorus losses to the atmosphere. Besides, the contribution of wheat seed to eutrophication and terrestrial ecotoxicity is high because SimaPro quantified the entire seed production process during LCA. In the densification stage, life cycle assessment reveals that the drying process contributes more to ozone layer depletion, GWP, abiotic depletion, photochemical oxidation, and acidification because of fuel used, while pelletizing has a high impact on acidification, fresh water aquatic ecotoxicity, human toxicity, and photochemical oxidation through electricity consumption and heavy metal use.

The choice of allocation methodology is essential for the outcomes. It is necessary to conduct sensitivity analysis on different allocation options. Physical allocation is recommended if allocation cannot be avoided. As a by-product of grain production, wheat straw has low economic value; therefore, its environmental burden is low when using economic allocation in LCA compared with mass allocation. Sensitivity analysis is also conducted to investigate key parameters in pelletizing and drying processes. They include pelletizing energy consumption, the type of fuel used in drying process, and moisture content of wheat straw before drying. The sensitivity analysis shows that reducing energy inputs of drying and pelletizing processes as well as decreasing the moisture content of raw wheat straw will significantly improve the environmental performance of a pellet plant.

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